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DYNAMICALLY INDUCED MESO-SCALE
VARIATIONS OF THE URBAN MIXING LAYER
DEPTH

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DYNAMICALLY INDUCED MESO-SCALE VARIATIONS
OF THE URBAN MIXING LAYER DEPTH

by

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PREFACE

This report contains the slightly revised text of a thesis presented by Mr. Timothy Spangler in partial fulfillment of the requirements for the Master of Science Degree in Atmospheric Resources.

Project METROMEX, a cooperative program between federal, state, university and private research groups, has been undertaken to examine the problem of inadvertent weather modification by an urban-industrial complex. The Project represents a broad, multi-disciplined approach to the problem. Initial field studies were begun in St. Louis during the summer of 1971 with the University of Wyoming personnel conducting a one-month field program during the month of August.

The research described by Mr. Spangler examines some basic considerations of dynamic and thermodynamic influences in an urban area. In particular, these influences are examined under conditions which would be favorable for the occurrence of convective precipitation. Observations made during August 1971 revealed the presence of a meso-scale distortion of the mixing layer depth over the St. Louis metropolitan area. Although somewhat inconclusive, an evaluation of various causal mechanisms suggests that surface and terrain influences played only a secondary role in producing the observed anomaly in mixing layer depth.

Although the relative importance of various dynamical and micro-physical influences on urban weather anomalies has not yet been ascertained, this work points to a dynamical feature which needs further examination in the continuing METROMEX studies.

R. A. Dirks

ABSTRACT

The dynamical effects of an urban surface on the airflow above it could be an important factor in meso-scale precipitation patterns. In order to evaluate the dynamical influences of an urban area, local variations in the mixing layer depth over metropolitan St. Louis are investigated. Variations in the height of a temperature inversion capping a deep mixing layer are used to measure the urban effect on the mixing layer depth. Case studies employing aircraft, pilot balloon and radiosonde data collected in Project METROMEX show that the St. Louis urban area produces a doming of the inversion layer over the city during the morning hours on certain summer days. It is concluded from observational and numerical modeling studies that the urban surface influence did not contribute significantly to the formation of the inversion dome but rather that a major influence existed within the upper regions of the mixing layer.

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I. INTRODUCTION

The Project METROMEX (METROpolitan Meteorological EXperiment), of which this report is a result, studied the St. Louis urban area with the following goals in mind:

- a. to study the effects of the urban area on the frequency, amount and intensity of precipitation,
- b. to identify the processes responsible for observed urban effects on weather,
- c. to isolate the factors which cause the observed effects and
- d. to determine the impact of urban-induced inadvertent weather modification on the populus of the urban complex.

The Project was directed by scientists from Argonne National Laboratory, the University of Chicago, Illinois State Water Survey and the University of Wyoming working in a cooperative program to study the general subject of inadvertent modification of weather by an urban-industrial complex.

There exist many possible influences of an urban area that could affect precipitation patterns. The dynamical influences of the urban topography, variations in frictional drag due to building structures and heating patterns produced by surface features and pollutants aloft could each contribute to modifying precipitation patterns. Micro-physical considerations such as changes in condensation and ice nucleus concentrations, modification of physiochemical processes in the cloud by urban produced effluents and the effect of polluted conditions on the coalescence mechanism of precipitation could also act to modify the precipitation process, resulting in the existence of a precipitation anomaly.

This research proposes to investigate the urban influence on the airflow within a deep mixing layer. Spatial and temporal variations in the height of a temperature inversion that frequently caps this layer will be measured. Such inversions are relatively persistent features of the atmosphere which reflect dynamic processes in the mixing layer. The variation of the wind field within the mixing layer will also be used to evaluate the dynamic processes taking place. Areas favorable or unfavorable for convective activity may be created by variations in the mixing layer depth and consequently those variations are important to satisfying the goals of Project METROMEX.

II. LITERATURE REVIEW

2.1 Urban Temperature Investigations

Prior to Project METROMEX, numerous investigations of the urban environment began building the knowledge of urban meteorology (see Table 2.1).

Renou (1862) found that downtown Paris temperatures were warmer than the temperatures measured at a rural station. In 1891, Hammon and Duenckel noted a 4.6F difference in the daily minimum temperatures between a downtown St. Louis station and a station in Forest Park (Hammon and Duenckel, 1902).

Mobile temperature transects were first made by Schmidt (1927) in the vicinity of Vienna and revealed evidence supporting the concept of the urban heat island. Since Schmidt's experiments, urban investigations have become more thorough and more sophisticated. Duckworth and Sandberg (1954) studied the California cities of San Francisco, San José and Palo Alto. In this study, it was first noticed that larger cities had a weak temperature gradient near the center and a strong temperature gradient near the perimeter of the urban area. Expanding on this, Ludwig (1968) found a definite cool inner core in the daytime surface temperature fields of Dallas and Fort Worth. This cooler inner core seems to be caused by the attenuation of solar radiation by the taller, larger buildings near the center of large cities.

From the studies of these researchers, the typical daytime urban surface temperature field can be pictured as having a strong temperature gradient near the outside, weaker near the center and reversing to a slightly cooler core in the area of tallest buildings.

The heat island anomaly has been attributed to three primary causal factors:

- a. the thermal capacity of building materials,
- b. the decrease of outgoing radiation flux during the night due to the insulating effect of air pollutants and
- c. the heat contribution from the burning of various fuels.

The relative importance of these factors has been changing over the last century as fuel usage varied and urban areas changed in size and composition. Variations in the magnitudes of the factors also occur geographically, seasonally and daily.

Table. 2.1. A partial list of urban meteorological investigations.

YEAR PUBLISHED	INVESTIGATOR	LOCATION	INSTRUMENTATION USED												PARAMETERS MEASURED									
			FIXED SURFACE STATIONS	AUTOMOBILE TRANSECT	WIRESONDE	RADIOSONDE	INSTRUMENT TOWER	AIRBORNE TRACER	TRACKING RADAR UNIT	PILOT BALLOON	INSTRUMENTED HELICOPTER	INSTRUMENTED AIRPLANE	RADAR-TRACE TETROON	LIDAR	TEMPERATURE	MOISTURE	WIND	PRECIPITATION	RADIATION	HAZE LAYER DEPTH	NUCLEI	POLLUTANT		
1895	ANGOT	PARIS					X							X										
1902	HAMMON, DUENCKEL	ST. LOUIS	X											X	X	X	X							
1927	SCHMIDT	VIENNA		X										X										
1929	PEPPLER	KARLSRUHE		X										X										
1936	MIDDLETON, MILLER	TORONTO		X										X										
1950	SUNDBORG	UPPSALA	X	X										X										
1954	DUCKWORTH, SANDBERG	SAN FRANCISCO, BAY AREA	X	X	X	X								X	X									
1961	DE MARRAIS	LOUISVILLE					X							X										
1963	POOLER	LOUISVILLE	X				X							X										
1964	ARNOLD	ST. LOUIS			X		X									X		X						
1966	POOLER	ST. LOUIS	X		X	X	X	X		X			X		X	X								
1966	DJORDJEVIC ET AL	DENVER	X		X						X			X	X	X	X							
1967	HASS ET AL	NEW YORK									X			X	X	X					X			
1967	HUTCHESON ET AL	CORVALIS		X								X				X								
1968	GEORGI	MANNHEIM - LUDWIGSHAFEN									X										X			
1968	BORNSTEIN	NEW YORK									X			X										
1968	LUOWIG	DALLAS - FORTWORTH		X										X	X									
1969	MUNN ET AL	TORONTO	X											X										
1969	CLARKE	CINCINNATI		X							X			X										
1969	FINDLAY, HIRT	TORONTO	X											X										
1971	ANGELL ET AL	COLUMBUS									X	X		X		X								
1971	OKE, FUGGLE	MONTREAL		X										X										
1971	EAST	MONTREAL												X				X						
1971	WOOD	AUSTIN	X	X								X		X										
1971	FONDA ET AL	BELLINGHAM		X										X	X									
1971	MCELROY	COLUMBUS		X			X	X		X	X	X	X	X	X	X		X			X			
1971	METROMEX	ST. LOUIS	X	X		X		X	X	X		X		X	X	X	X		X		X			

2.2 Urban Effects on Airflow

The primary dynamic effect during strong wind conditions has been hypothesized to be due to the increased roughness of urban areas. This may certainly be the case when the urban area is surrounded by grassland or farmland. However, the roughness properties of forests may be typical of urban structures (Yamamoto and Shimanuki, 1964; Lettau, 1969) so that significant frictional effects exist only in small areas of very tall buildings when wooded land surrounds an urban area.

Summers (1965) and Clarke (1969) envisaged a layer of unstable warm turbulent air being sandwiched between two stable layers downwind

of a city. This urban heat plume was the object of a numerical model of the nocturnal heat island developed by McElroy (1971). The model predicted a deeper adiabatic layer over the urban area with the surface air becoming stable downwind. Observations of the development of the adiabatic layer over Columbus, Ohio, agreed well with the model predictions.

It is also useful to consider an urban area as resembling a heated island surrounded by water. This is an advantage because the effects of an island on airflow are similar to those produced by an urban area and studies of islands are more easily conducted free from extraneous disturbances. Airflow over a flat heated island was theoretically studied by

Malkus and Stern (1953) who used a linear model to define the flow across a narrow, infinitely long island. The solutions showed the mean streamlines of flow to be deformed into a mountain-like shape over the lee shore boundary of the heat source. This is called the "equivalent mountain" that is produced by a heated island. An observational study of Anegada Island by Malkus (1963) yielded airflow perturbations very similar to the island airflow model.

With light regional winds, the urban area may be capable of maintaining a closed meso-scale circulation. Such an urban induced circulation would be classified as antitriptic. The warmer urban area creates slightly lower pressure and thus a pressure gradient from outside toward the center of the urban area is formed. This would indicate, in the absence of other circulations, a radial type of circulation with air being driven toward the center of the city at low levels, and reverse flow aloft resulting from a reverse pressure gradient at that level. Duckworth and Sandberg (1954) noticed the 'crossover' sounding in Palo Alto where the urban area was capped by air that was cooler than the air at the same level over a rural environment.

Some limited observations have been made of the urban circulation. Arnold (1964) documented this type of circulation through the use of the two instrumented towers and photography in St. Louis. He found that under a strong surface inversion, an easterly component wind was capped by a westerly component at the 150 m level. Pooler (1963) showed a nighttime surface wind drift towards the center of the city of Louisville, as did Georgii (1968) for Frankfurt, Germany, and Okita (1960) for Asahikawa, Japan. All of these studies were of cities in river valleys and could have had significant drainage wind effects masking the actual urban circulation. Georgii (1968) found that when the mean geostrophic wind exceeded $3-4 \text{ m sec}^{-1}$, an urban driven circulation was prevented from forming. Measurements of return flow aloft have been provided primarily by the tower measurements of Arnold (1964) and Pooler (1963). Despite those measurements, evidence of the three-dimensional structure of the urban circulation is still lacking.

Recent results of a numerical model by Delage and Taylor (1970) showed the acceleration of air toward the urban center at the surface with a return flow at about 1000 m. No attempt was made to relate the model results to observations.

2.3 Urban Effects on Temperature Inversions

The effects of turbulence, heating and urban circulations are especially significant when applied in the presence of temperature inversions. Davidson (1967) found that the presence of surface and elevated inversions significantly influenced the concentrations of SO_2 in New York, and thus the buildup of air pollutants. De Marrais (1961) concluded from tower data that the heat island of an urban area has considerable effect on the vertical temperature differences observed at night, so that the normal daily range of stability conditions encountered over an urban area is much smaller than that over open country. Although De Marrais' research showed that a surface inversion is more likely to be elevated over the city, he failed to consider effects above the surface inversion. An inversion at levels 500-1500 m may be very significant to the mixing of pollutants, especially during the daytime, and may also reflect, through its height fluctuations, dynamic effects of the urban area.

Several studies have sought to develop techniques for predicting the depth of the daytime mixing layer which may be capped by a temperature inversion. A theoretical work by Anderson (1971) concluded that frictional effects of an urban area do not significantly affect the depth of the mixing layer while thermal and topographical effects do. Wuerch (1971), in St. Louis, developed criteria for forecasting mixing layer depths based on a statistical study of St. Louis data. He considered the surface inversion to be of minor importance, and measured mean wind speeds between the surface and an inversion capping the mixing layer. Analyses of daily radiosondes showed that by mid-day the effective mixing layer extended to the capping inversion. The study also found that for low wind speeds, the early morning urban wind field was not spatially uniform contrasting with uniform winds within the well-mixed layer by mid-day.

Since inversions act as caps to convective clouds, variations in inversion height could significantly affect the location or occurrence of convective activity. If an inversion is higher in one location than another, a buoyant parcel of air has a better chance to reach saturation as it rises than one in a location where the inversion is low. The saturated parcel would also have a better chance of breaking through the inversion cap. From these considerations, the spatial variations of the height of a temperature inversion may be important to the problem of urban influences on convective precipitation patterns.

2.4 Urban Effects on Precipitation

Urban effects on precipitation in North America have been primarily documented by Landsberg (1956) and Changnon (1961, 1962, 1968a, 1968b, 1969a, 1969b) although early researchers such as Ashworth (1929) discovered urban precipitation anomalies. Dettwiller (1968) showed that for the period 1953-1967, the occurrence of daily rainfall in Paris was 31% greater Monday through Friday than it was on Saturday or Sunday.

In the United States, Changnon has published reports of precipitation anomalies in several midwest cities. The most controversial of these anomalies was reported at La Porte, Indiana. Changnon (1968a) found that La Porte had 31% more precipitation, 38% more thunderstorms and 264% more hail days than surrounding stations. Changnon (1969b) also found a 5% increase in precipitation over Chicago (note that 60% of this increase was in the warmer half of the year) and a 7% annual increase in St. Louis.

The St. Louis anomaly has recently come under greater scrutiny by Project METROMEX. Changnon (1970) looked at the heavy rainfall frequencies (two or more inches) for the St. Louis area. He distinguished the following types of areas based on radar observations of storm motions: upwind, downwind, urban-industrial complex and an area just downwind of the urban-industrial complex. Changnon found that the area just downwind of the urban-industrial complex (his 'Major Effect' area) had 54% more heavy rain days than the far upwind or urban-industrial complex areas. It had 38% more heavy rain days than the far downwind area. Changnon found from the climatological data for the period 1951-1968 that there was an 11% increase in the average seasonal rainfall on weekdays in his Major Effect area of St. Louis compared to the far downwind area. From his research in the St. Louis area, Changnon made the following five general conclusions:

- a. Urban effects produced annual precipitation increases of 5-31%,
- b. Increases came in all seasons but more than half of the increases occurred in the warm half of the year,
- c. Warm season increases occurred primarily on rain days of 0.25 inches or more,
- d. The major increase was not directly over the urban-industrial complex but displaced immediately (0 to 40 km) downwind and
- e. The precipitation increase was primarily due to rainfall resulting from convective type clouds.

Recently, Changnon (1972) found through further climatological investigations that the St. Louis anomaly was associated with daytime or early evening storms. Morgan (1972) also found that the anomaly was not associated with fronts, but occurred with deep mixing layers.

The results of all urban investigations to date indicate the need for further research into urban dynamic influences. Since the St. Louis precipitation anomaly is associated with summer, convective, daytime or early evening, non-frontal rain storms, an investigation of daytime urban effects extending to convective cloud base is a necessity. Many urban dynamic influences can be most easily detected by measuring their effect on inversion surfaces aloft. The following chapters describe a study of urban induced meso-scale variations in the urban mixing layer depth and relates these variations to possible dynamic influences of the urban area.

III. RESEARCH METHODS

3.1 General Land Use and Terrain Around St. Louis

Commensurate with the goals of Project METROMEX, St. Louis was chosen as the urban area to be studied because of its smooth topography and the lack of any significant large bodies of water nearby. The most prominent topographical feature of the St. Louis area is the river valley (Figure 3.1). The principal urban area is located about 16 km south of the confluence of the Missouri and Mississippi Rivers. The Mississippi River separates Missouri and Illinois (approximately along a north-south line) with a heavy concentration of industry along both banks. The river elevation is approximately 122 m.

To the west of the river, the land rises to 150 m in downtown St. Louis and to 180 m on the western extreme of the research area with an area extending to nearly 285 m some 15 km southwest of the city. In this region the Meramec River winds through sharp ridges and valleys. Beyond Kirkwood, just west of St. Louis, the land use is largely agricultural with numerous wooded areas. To the northwest of St. Louis the bottomland consists of small farms and frequent wooded areas.

To the north of St. Louis steep bluffs lie along the east bank of the Mississippi River. Eastward above these bluffs lies a flat agricultural area. To the east of St. Louis lies a fairly flat flood plain with an elevation of approximately 150 m. In this basin, in addition to industrial areas, there

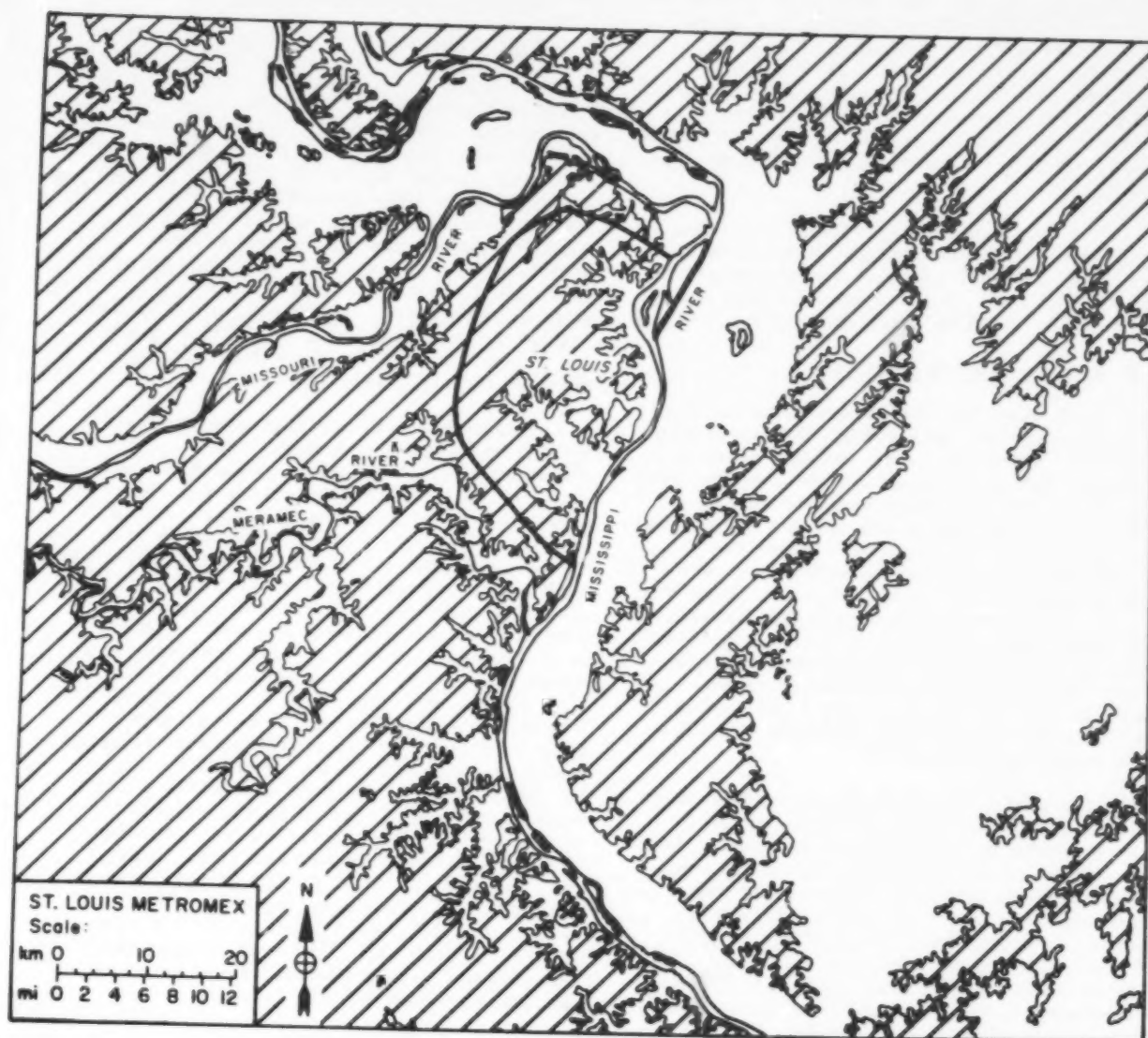


Figure 3.1. Contour map of the St. Louis region. Contours are in 100 foot intervals with terrain above 500 feet indicated by slanted lines.

are considerable open swampy spaces with only occasional woods. Beyond the flood plain, in a gentle arc approximately 16 km east of the river, lies a 165 m to 215 m ridge. To the east of this ridge, the land is flat with occasional groves of trees. The land use is primarily agricultural. Southeast and south of St. Louis there are rolling hills, farms and bottomland near the Mississippi River.

3.2 Description of St. Louis Urban Area

Greater St. Louis has a population of over 1.5 million people. On the Illinois side of the Mississippi River, still in the low river

valley, lie East St. Louis and Granite City totaling 150,000 people. On the higher ground beyond the ridge to the east and north lie the smaller cities of Belleville, Collinsville, Edwardsville and Alton with populations totaling 150,000.

The downtown area of St. Louis has numerous buildings taller than 10 stories. The two tallest buildings, the Civil Courts Building and the Bell Telephone Building, rise 111 m to extend to an altitude of 245 m above sea level. A small area of tall buildings also exists in Clayton. Forest Park, just to the east of these tall buildings, is a large

sporadically wooded area about 2 km x 5 km in size. The urban area outside of the built-up downtown proper has numerous large deciduous trees lining the streets and is interspersed with smaller parks and playground areas. The contrast between the amount of trees in suburban areas and downtown St. Louis can be seen by comparing Figure 3.3 with Figure 3.2.

Heavily industrialized areas lie along both banks of the Mississippi River (See Figure 3.2), with the heaviest concentrations on the East Bank of the river extending from Alton south to 15 km south of East St. Louis.

3.3 Surface Observing Systems

Both fixed and mobile methods were used to gather surface meteorological data during selected case-study days. Surface temperature and dew point data were obtained through the use of two specially equipped mobile weather stations which sampled the air approximately 3 m above the ground. These two parameters were recorded continuously on a twenty-four channel chart recorder. When the mobile units were stationary, wind direction and wind speed sampled at 6 m were also available as well as several other measurements taken by instruments pertinent to cloud physics studies (see Appendix A for a more complete description and photograph of the mobile weather stations).

The mobile units sampled temperatures by making transects across the city, planned so as to establish a route approximately under the flight of the Wyoming aircraft (Figure 3.4). The direction of the transect was determined by the prevailing surface winds prior to the start of the aircraft flight. It was always noted when the mobile unit was in heavy traffic, over any body of water or passing an apparent source of great heat. Very little fluctuation of temperature was attributed to any of these sources when the vehicle was moving over 15-20 mph. The mobile units also contained facilities for single theodolite tracking of pilot balloons. Unfortunately, only one mobile unit was available for the second half of August.

Additional surface data were available from the National Weather Service Station at Lambert Field. Hourly observations were also taken by four Air Force double theodolite teams (locations shown in figure 3.4) and by the University of Wyoming radiosonde crew near Pacific (46 km southwest of St. Louis) during the daily six hour periods these crews were in the field.

3.4 Wind and Radiosonde Observations

During the month of research, a radiosonde was operated by the University of Wyoming at an abandoned Nike Missile site located 13 km south of Pacific, Missouri (the facilities were kindly provided by the Meramec Valley R-III School District). The sonde was routinely tracked to 400 mb and was launched twice daily at 0700 and 1200 CDT. The National Weather Service also routinely launched a slow rise radiosonde at the Jefferson National Monument (Gateway Arch) at 0700 and 1230 CDT with an occasional mid-morning launch under the Environmental Meteorological Support Unit Program (EMSU). These sondes were tracked to 700 mb and tracked visually by one theodolite.

Routinely, wind profiles were measured by double theodolite methods. Four Air Force, Air Weather Squadron teams were employed to take double theodolite tracks from four sites located approximately on the corners of a square within the principal urban area (shown in Figure 3.4). Over a six hour period, each crew launched 4 balloons inflated to rise about 230 m min⁻¹. Early morning and early evening time periods were studied. Tracks were attempted to 4600 m, with readings taken every 30 sec, although most early morning tracks were unsuccessful above 1500 m. Single theodolite tracked pilot balloons were launched from the mobile weather stations simultaneously with those launched by the Air Force teams. A single theodolite pilot balloon was also launched by the Wyoming radiosonde crew at Pacific to coincide with the other launches across the city. Every day, at 0000 CDT and 1200 CDT, single theodolite pilot balloons were tracked by the Lambert Field National Weather Service personnel. In addition, the Arch radiosondes were tracked with a theodolite and provided wind measurements at that location.

3.5 Aircraft Measurements

University of Wyoming scientists operated an updated C-45H/A twin-engine Beechcraft in Project METROMEX. The sensors associated with the aircraft system and their range, accuracy and resolution are described in Appendix B. The primary aircraft sensors employed in St. Louis measured temperature, dew point and turbulence (see Appendix B).

For airflow research purposes, the aircraft was flown on selected early mornings with the opportunity for subsequent flights if conditions were favorable for investigation of the urban influence. Generally cloudless conditions were sought with a distinct stable layer (preferably an inversion) capping the mixing layer at 500-2000 m msl.



Figure 3.2. Looking northeast past the Jefferson National Monument (Gateway Arch) over St. Louis, Missouri (Photograph by August H. Auer, Jr.)



Figure 3.3. Looking northwest from over Forest Park in St. Louis.

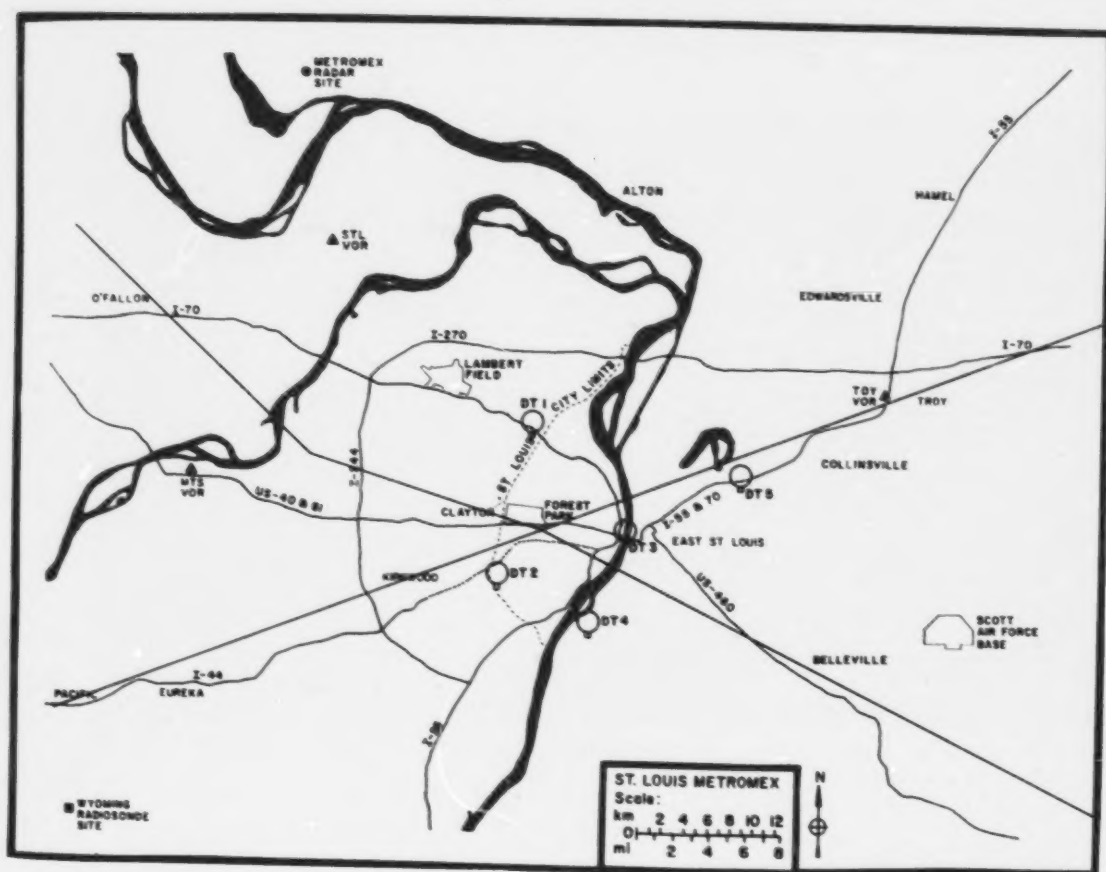


Figure 3.4. Map of St. Louis area with a balloon symbol indicating a double theodolite site and the northeast-southwest and northwest-southeast lines showing the aircraft flight paths. Double theodolite site number three was located at the Jefferson National Monument (Gateway Arch).

The aircraft always flew a sounding while climbing out of Alton Civic Memorial Airport and consequently could determine the height of stable layers and inversions during this ascent. The aircraft would then fly several levels below, above and through the primary inversion layer to determine its deformation and height across the city. At the end of each horizontal transect, spiraling ascents and descents were made. Additional valuable information was obtained from low-level flights across St. Louis at approximately 150 m agl (330 m msl). The operational plan of the aircraft sought to study the low-level variability of the adiabatic layer often present over the urban area, the variable depth of this layer and the measurement of urban effects at convective cloud base.

The aircraft data were recorded on magnetic tape in addition to being displayed in the cockpit for real time use by the meteorologist on board.

3.6 Aitken Nucleus Measurements

A Gardner Counter aboard the University of Wyoming aircraft was used to measure concentrations of Aitken nuclei under the direction of the meteorologist on board. The counter uses a rapid expansion causing adiabatic cooling to obtain excessive supersaturation. After saturation, the Aitken nuclei act as condensation nuclei and are optically counted. This method can detect particles between 0.001 and 0.1 micron diameter. Measurements of all sizes of aerosols by Junge (1952) indicated that Aitken nuclei represent essentially the total particulate concentration. Junge found average Aitken nuclei concentrations of 10^4 cm^{-3} for urban air while larger nuclei had concentrations more than two orders of magnitude less. The mass of particles in any size range was found to be nearly the same. These results enable Aitken

nucleus counts to be used synonymously with total particulate concentrations. Aitken nucleus concentrations in this study will be used as tracers and indicators of static stability. Each concentration is the result of three readings taken at 15 second intervals and arithmetically averaged.

3.7 Available Supplementary Data

Valuable additional data for this thesis were provided by the Stanford Research Institute whose personnel operated a Mark VIII lidar in conjunction with Project METROMEX (Uthe, 1972). One lidar pulse or observation provides data on atmospheric scattering in the direction of the pulse. From that observation the researcher can determine, in relative terms, the distribution of particulates in the atmosphere. Similar to radar, lidar reports movements and locations of particulate concentrations or visible clouds. The depth of the turbid layer can be measured in the urban areas, and the depth can then be related to inversions and thermal stratification. Studies by Viezee and Oblandas (1969) concluded that internal stratifications of optical density within the aerosol layer were directly related to thermal structure such as inversions and stable layers.

Gambling and Bartusek (1972) showed that the strength of a backscattered lidar signal depended heavily on the humidity present in the aerosol layer. This implies that the lidar primarily detects hygroscopic particles. Thus, the weakening of a lidar signal could indicate drying as well as fewer aerosols being present.

For Project METROMEX, the Mark VIII lidar was operated both as a stationary instrument in downtown St. Louis and as a mobile unit taking measurements along a transect across the urban area with the instrument pointed vertically. The lidar data for this study will be used as a measure of the depth of the mixing layer which is capped by a temperature inversion.

Additional data were available through other cooperating METROMEX groups. Argonne National Laboratory scientists directed the operation of ten Air Force double theodolite teams in boundary layer studies. The Illinois State Water Survey operated a forecasting center and weather radars at Pierre Marquette State Park northwest of St. Louis. They also maintained a network of recording rain gauges, hail pads and temperature and wind recording stations located throughout the St. Louis urban area. Additional aircraft flights were made by the University of Chicago although none of the data from those flights have been used in this report.

IV. RESEARCH RESULTS

4.1 Research Approach

Several experiments in Project METROMEX were designed to examine the temporal and spatial variability of dynamic influences over an urban area. Both light and moderate wind situations were studied during days when a distinct inversion or stable layer capped the convective mixing layer. The data presented in this chapter were collected in conjunction with the research on light wind days. August 12, 1971 was such a day and was the object of an intensive day-long research effort.

4.2 August 12, 1971, Case Study

Synoptic Conditions. The St. Louis area was under the influence of a weak surface high centered over Ohio. Low-level flow varied from southeast to northeast at approximately 5 m sec⁻¹ while the flow above 2500 m* was from the northwest at 4 m sec⁻¹. The 500 mb contour gradient over Missouri was extremely weak. Morning soundings taken by the National Weather Service at Peoria, Illinois, (240 km north of St. Louis) and Salem, Illinois, (120 km east of St. Louis) both showed temperature inversions at approximately 1200 m capping the mixing layer at that level. By early evening the inversion at both Salem and Peoria ascended 300 m. The Salem inversion, formerly weak, became stronger. Soundings taken at Monett, Missouri, (400 km southwest of St. Louis) found a stable layer capping the mixing layer at 1400 m in the morning. By evening the mixing layer warmed 4K and was 2500 m deep capped at that level by a stable layer.

Data collected on August 12 is most easily divided into four periods coinciding with the four aircraft flight periods. The periods are defined as early morning (0610-0930 CDT), mid-day (1100-1300 CDT), mid-afternoon (1503-1735 CDT) and early evening (1845-2035 CDT).

Early Morning Flight Period. Aircraft soundings taken at the ends of horizontal flight paths across St. Louis indicated temperature inversions at approximately 1500 m outside the city. An inversion denotes a strong stable layer where temperature is either isothermal or warms with height. Data from the National Weather Service radiosonde launched at the Gateway Arch also reveal a temperature inversion at approximately 1500 m over the urban area. The layer immediately under the 1500 m inversion was adiabatic becoming slightly stable below 1000 m with a shallow surface inversion. During a three-hour period, four levels were flown across the city along the southwest to northeast line (Pacific-Troy)

* All heights pressure altitude above mean sea level.

shown in Figure 3.4. A flight at 1680 m did not intersect the inversion layer, thus putting a restriction of 50 m on the possible upward displacement of the inversion at 0900 CDT. It is concluded that the inversion was essentially horizontal across St. Louis along a southwest to northeast line as depicted in Figure 4.1. Rural aircraft soundings taken over Troy at 0630 CDT and again at 0930 CDT found that the inversion remained at the same level (1480 m) while over Pacific from 0715 to 0830 CDT it had subsided only 45 m (1560 m to 1515 m), indicating some steadiness of the inversion height.

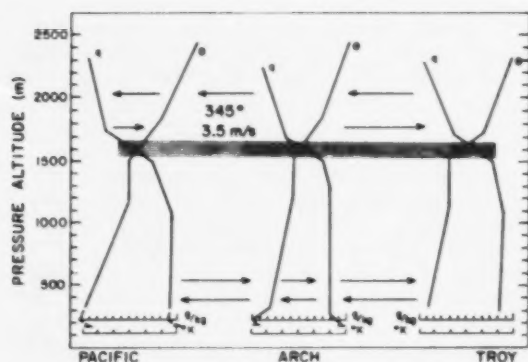


Figure 4.1. Inversion height over St. Louis on 12 August 1971 as measured by aircraft soundings at Pacific (0700 CDT) and Troy (0640 CDT), the Gateway Arch radiosonde (0700 CDT) and horizontal aircraft flights shown by arrows. Soundings show potential temperature (θ) and specific humidity (q) with scales in unit intervals.

Plots of the aircraft data for the four flight levels are depicted in Figure 4.2. The lower three flights indicated only small potential temperature fluctuations (~ 1 K) and moisture fluctuations (~ 1 g/kg) over the urban area. The lowest flight (370 m) found the urban air west of the Mississippi River about 0.5 K warmer than rural air. The flight 150 m higher showed a gradual warming of the air from northeast to southwest with the air over Pacific 0.5 K warmer than over Hamel. Aircraft flights below the 1500 m inversion indicated a uniform horizontal distribution of moisture. Above the inversion, at 1680 m, air to the southwest was more moist (~ 2 g/kg) than air over the urban area and warmer (~ 1 K) to the northeast of the urban area. A 1980 m flight found the air more moist over the urban area (~ 1 g/kg) and temperatures fairly constant. Air to the northeast of St. Louis cooled 2.0 K from 0630 to 0930 CDT within the lowest 900 m while 0.5 K of heating occurred

to the southwest of St. Louis in the same layer from 0715 to 0830 CDT. Surface temperature transects taken underneath the aircraft flight path measured a +3.0°C temperature increase from rural to urban locations at approximately 0630 CDT.

The pilot balloon (pibal) wind measurements at 0600, 0730 and 0900 CDT are shown in Figures 4.3, 4.4 and 4.5. A surface wind measurement represents an average for the first 30 seconds ($\sim$ surface to 90 m) of the balloon ascent. At 0600 CDT (Figure 4.3) the winds were quite uniform at the surface and 450 m. All the stations showed some wind shift at 750 m, probably caused by a thermal gradient. Comparisons at 1000 m of northeast aircraft soundings to southwest aircraft soundings indicated the southwest air to be 1.5 K warmer. This thermal gradient, which was not apparent at the 520 m flight level, could have induced the wind shifts at 750 m. By 0730 and 0900 CDT (Figures 4.4 and 4.5) the lower 750 m appeared to have become homogeneous with mixed winds occurring at 1050 m and all the stations shifting at the inversion (1500 m) to approximately 345° at 4 m sec^{-1} .

Aitken nucleus counts were taken periodically during the aircraft flight and are shown in Figure 4.6. The counts revealed homogeneous concentrations to the southwest, within the stable layer below 1000 m. The higher counts at 900–1300 m over Troy were taken two hours later than the low-level counts over the urban area and reflect the breaking up of the surface inversion with the resulting upward flux of particles.

Mid-Day Flight Period. Aircraft flights along the northwest-southeast line shown in Figure 3.4 revealed the inversion structure shown in Figure 4.7. Over downtown St. Louis, the inversion remained at 1500 m but over the rural areas both northwest and southeast of the city, the inversion had lowered nearly 500 m. Over Belleville a slightly stable layer existed above 880 m with the inversion at 1060 m. Over O'Fallon, Missouri, the inversion was found at 1050 m. Although it revealed no inversion of temperature, the Pacific radiosonde helped to complete a more three-dimensional picture by indicating that the top of the adiabatic layer and a severe moisture decrease occurred at 950 m. A transect taken by the Stanford Research Institute lidar unit during the period 0940–1045 CDT found that the haze layer extended from 1500 m over downtown St. Louis to 1400 m at the western edge of the city (heights converted to pressure altitude) with a smooth upper boundary. Those lidar measurements of the top of the haze layer indicated that the inversion was probably becoming domed during mid-morning.

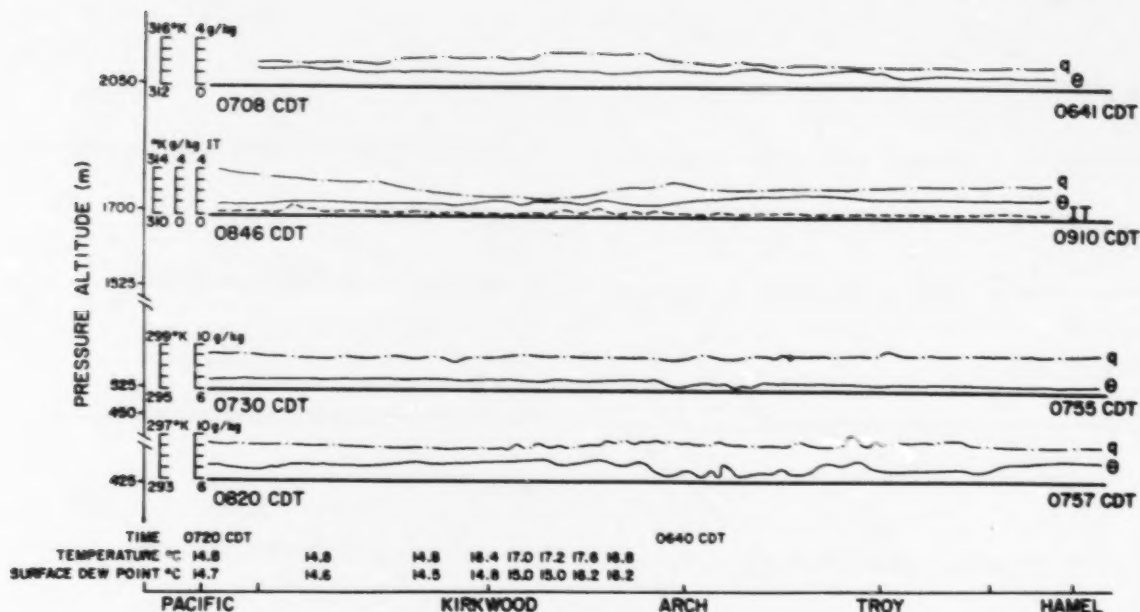


Figure 4.2. Aircraft flight data taken along a southwest to northeast line over St. Louis on 12 August 1971. Unit scales of potential temperature (θ), specific humidity (q) and turbulence (IT) are at the left of each flight level. Where turbulence is absent, it was approximately zero for the entire flight. Surface transect data are shown at the bottom with data available for only half of the city.

Aircraft-lidar comparisons showed excellent correlation between the top of the adiabatic layer and the top of the haze layer measured by the lidar. Pibal wind measurements (Figure 4.8) revealed a wind shift and speed minimum in the vicinity of the inversion although, through rise rate inaccuracy, the height of such a measurement could easily be off by 10% or 150 m at the inversion height. All of the aircraft soundings, radiosonde and lidar data for the mid-morning period point to the fact that the temperature inversion over St. Louis was domed at 1200 CDT.

At the surface, rural to urban temperature differentials were less than 1.0C at 1100 CDT (see Figure 4.9). Fixed point surface measurements at 1100 CDT showed no temperature difference from the Gateway Arch to Pacific, but the surface stations to the west of the river within the downtown proper were slightly warmer (~ 0.5 C).

Examination of the aircraft soundings in Figure 4.7 shows that a horizontal aircraft penetration of the inversion layer would encounter steep gradients of moisture and somewhat smaller gradients of potential temperature. The aircraft flight data for the 1060 m mid-day flight level shown in Figure 4.9 indicates that the aircraft penetrated the inversion layer at the rural extremities of the transect. Between Lambert Field and

O'Fallon, at 1060 m, moisture and potential temperature appeared to fluctuate out of phase, indicating that the aircraft was within the lowest region of the inversion layer. During an aircraft sounding over Belleville just prior to the transect at 1060 m, the inversion was located at 1060 m. On the 1060 m transect, when the aircraft was below the inversion, as indicated by fairly constant moisture, the air over St. Louis proper was 0.5K warmer than air over Lambert Field or the Mississippi River. An aircraft flight at 460 m showed increased moisture northwest of St. Louis when compared with the southeast half of the flight. The air over St. Louis was approximately 0.5K warmer than rural air at 460 m. Both the 1060 and 460 m flight levels encountered turbulence values ($\epsilon^{1/3}$) of 3.0-4.0, indicating that vigorous mixing was taking place (see Appendix B).

The Gateway Arch radiosonde at 1230 CDT revealed an isothermal surface layer 34 m deep topped by a 250 m superadiabatic layer. The Pacific radiosonde (launched on a hill) revealed a 300 m superadiabatic surface layer. The downtown isothermal surface layer could reflect the effects of tall buildings discussed in Section 2.1 or an effect of the Mississippi River, although the latter is a more doubtful influence since the measured water temperature was the same as the air temperature (29C).

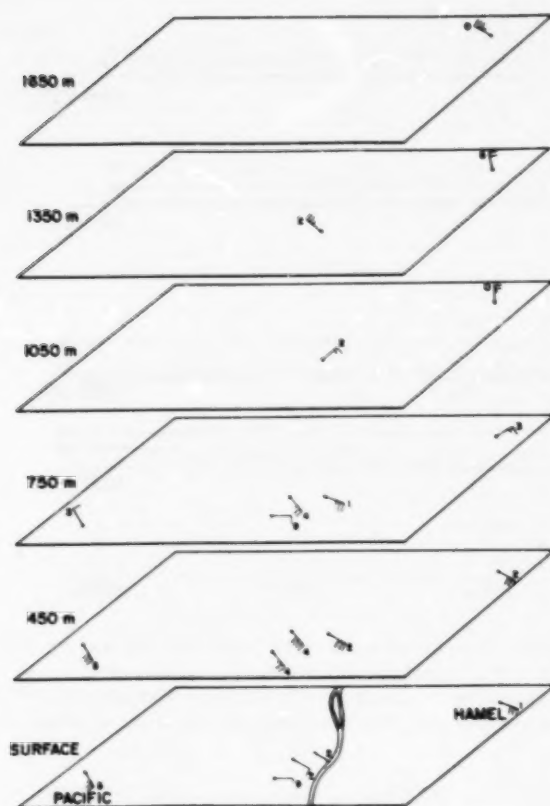


Figure 4.3. Wind profiles for 0600 CDT, 12 August 1971. Each full wind barb is 1 m sec^{-1} and a flag represents 5 m sec^{-1} .

The winds measured during the period 1130–1230 CDT are shown in Figure 4.8. They reveal very uniform winds in the lowest 600 m. Above this, but below the inversion dome, winds are variable. Above the inversion (see Figure 4.7), they again were uniform from the northwest.

Aitken nucleus concentrations are displayed in Figure 4.10 and reveal that nuclei were apparently transported out of the region above the inversion during the morning. The surface concentrations were the same as the early morning concentrations at the same level although along a different flight path. They indicate that thermal turbulence was not yet transporting nuclei away from the surface at a faster rate than their production.

Mid-afternoon Flight Period. By late afternoon the mixing layer deepened by 520 m over the rural areas. The inversion was apparently still domed at 1600 CDT along a northwest-southeast line (Figure 4.11) although somewhat less than at 1200 CDT. A 1680 m flight passed into the mixing layer over urban St. Louis but on the rural segments of the flight the aircraft was within the inversion layer. The aircraft data again indicated large

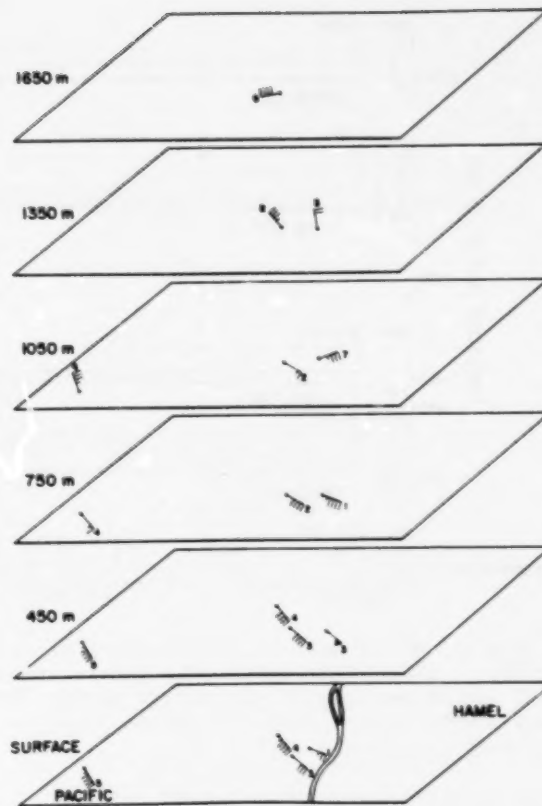


Figure 4.4. Wind profiles for 0730 CDT, 12 August 1971. Each full wind barb is 1 m sec^{-1} and a flag represents 5 m sec^{-1} .

($\sim 5\text{--}6 \text{ g/kg}$) wave-like fluctuations of moisture, 2 to 3K temperature oscillations and turbulence values of 2.0–4.0 within the inversion layer. To the northwest, 5 km east of O'Fallon, the aircraft was definitely out of the inversion layer but entered the inversion layer again further to the west of O'Fallon. This would suggest that the inversion began to rise again farther away from St. Louis. That could be an indication that the rural inversion subsidence was an urban induced feature.

A flight at 1980 m passed into the inversion layer for a brief time over St. Louis but not into the mixing layer. Turbulence values were less than 1.5 except when reaching 3.0 over downtown St. Louis as the aircraft penetrated the inversion layer. The aircraft again appeared to enter the inversion layer west of O'Fallon at 1980 m confirming the 1680 m measurement. Measurements taken by lidar agreed very well with aircraft measurements and showed the inversion dome to extend to 2050 m where the aircraft flight path crossed the Mississippi River. The maximum height of the mixing layer (2300 m) was apparently displaced 4.8 km northeast of the aircraft path over downtown St. Louis. The distribution of

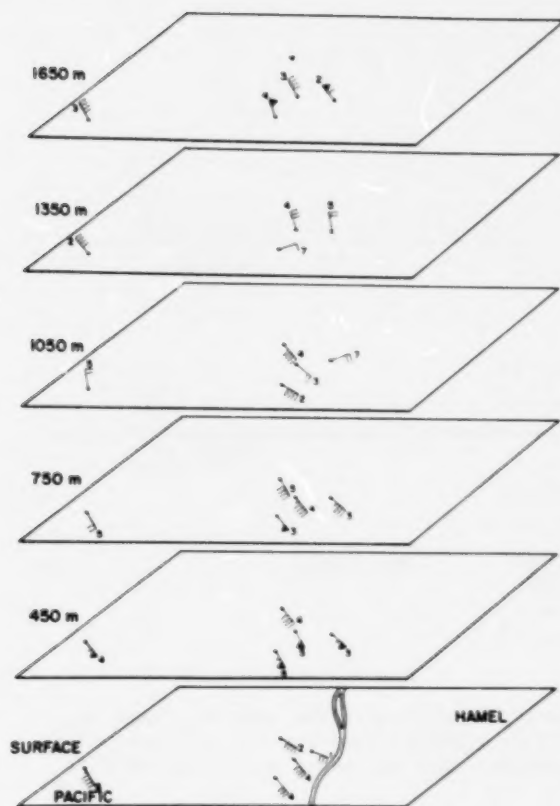


Figure 4.5. Wind profiles for 0900 CDT, 12 August 1971. Each full wind barb is 1 m sec^{-1} and a flag represents 5 m sec^{-1} .

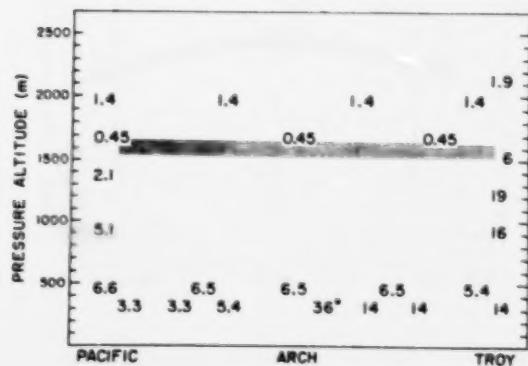


Figure 4.6. Corrected Aitken nucleus concentrations in units of 10^3 cm^{-3} taken during the flight period 0610-0930 CDT, 12 August 1971. The asterisk indicates sample collected in a visible plume.

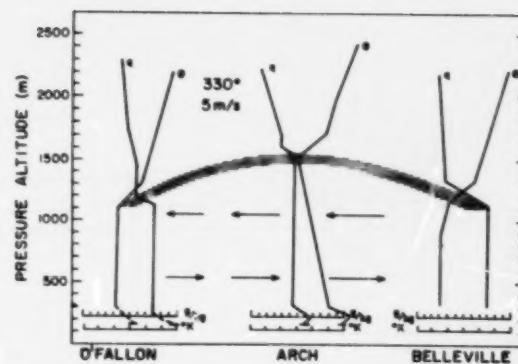


Figure 4.7. Inversion height over St. Louis on 12 August 1971, as measured by aircraft soundings at O'Fallon (1215 CDT) and Belleville (1130 CDT), the Gateway Arch radiosonde (1230 CDT) and horizontal aircraft flights shown by arrows. Soundings show potential temperature (θ) and specific humidity (q) with scales in unit intervals.

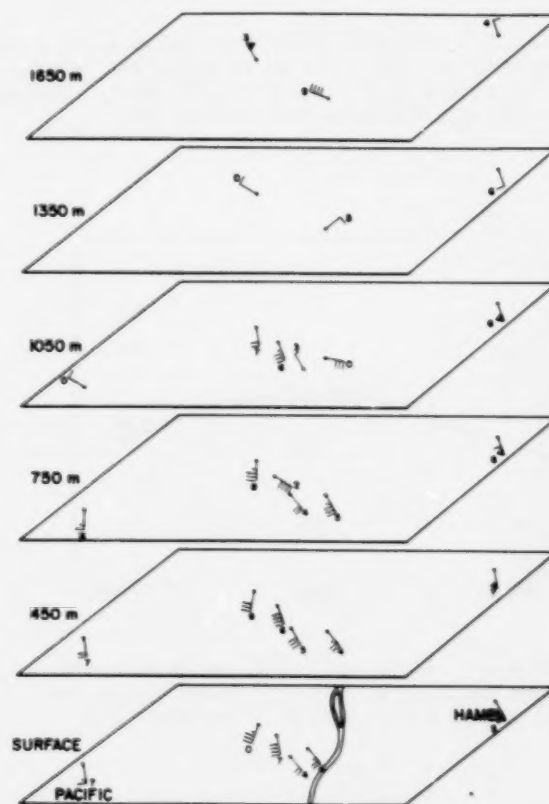


Figure 4.8. Wind profiles for 1130 CDT, 12 August 1971. Each full wind barb is 1 m sec^{-1} and a flag represents 5 m sec^{-1} .

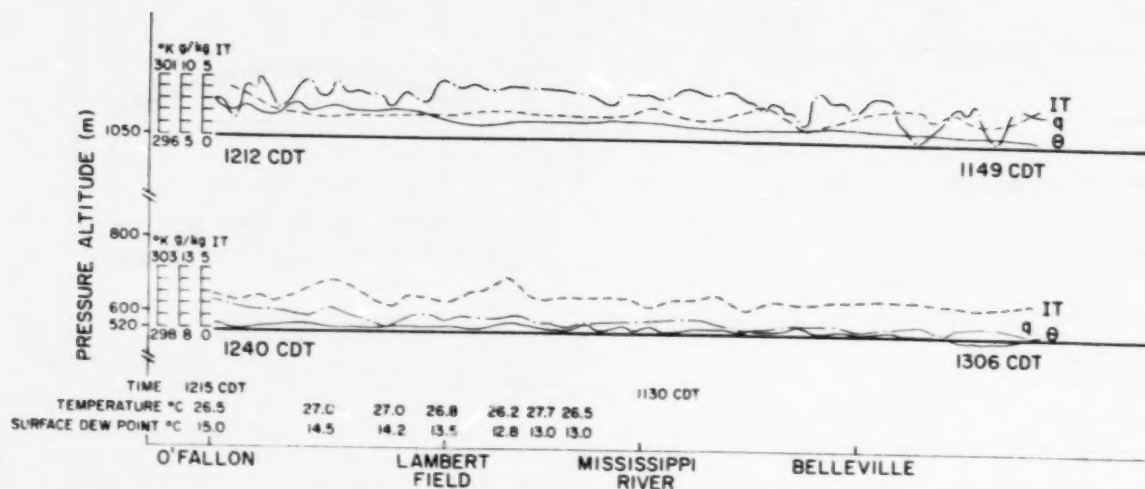


Figure 4.9. Aircraft flight data taken along a northwest to southeast line over St. Louis on 12 August 1971. Unit scales of potential temperature (θ), specific humidity (q) and turbulence (IT) are at the left of each flight level. Surface transect data are shown at the bottom with data available for only half of the city.

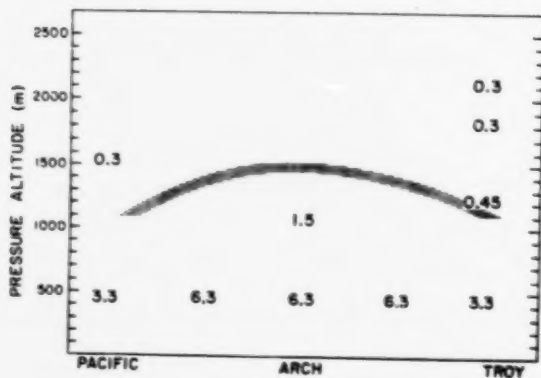


Figure 4.10. Corrected Aitken nucleus concentrations in units of 10^3 cm^{-3} taken during the flight period 1100-1300 CDT, 12 August 1971.

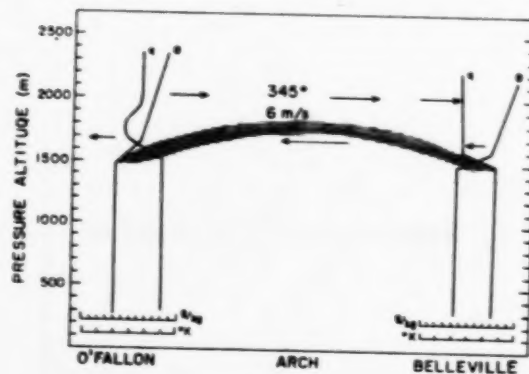


Figure 4.11. Inversion height over St. Louis on 12 August 1971, as measured by aircraft soundings at O'Fallon (1615 CDT) and Belleville (1530 CDT), and horizontal aircraft flights shown by arrows. Soundings show potential temperature (θ) and specific humidity (q) with scales in unit intervals.

Aitken nucleus concentrations in Figure 4.12 showed a wide dispersion of nuclei except for one high concentration measured within the inversion layer over the city. The few available wind measurements indicated that the air motion was still from 180-220° at approximately 2 m sec^{-1} within the mixing layer.

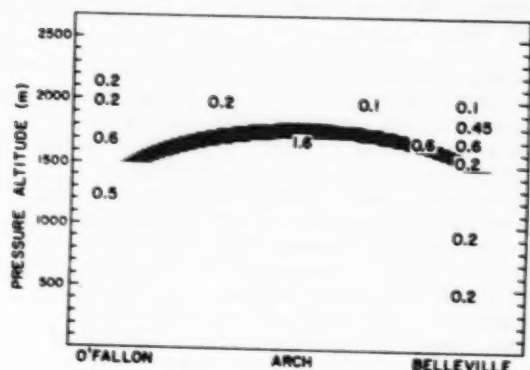


Figure 4.12. Corrected Aitken nucleus concentrations in units of 10^3 cm^{-3} taken during the flight period 1505-1735 CDT, 12 August 1971.

Early Evening Flight Period. Figure 4.13 indicates the apparent southwest to northeast profile of the inversion during the last flight of the day. Aircraft soundings during that flight (1845-2035 CDT) showed that a cooling of 1.0K occurred in the lower 1060 m causing a weak stable layer at 1060 m. The primary inversion over rural areas, both to the southwest and northeast, was located at 1370 m at 1900 CDT, down from 1530 m at 1600 CDT. A horizontal flight path at 1680 m passed into the inversion layer over downtown St. Louis and again over Eureka (southwest). During the times within the inversion, the turbulence read approximately 3.0, while it was less than 0.5 above the inversion. High values of turbulence were encountered whenever the aircraft was penetrating the inversion layer throughout all of the four flights on 12 August. A northeast to southwest flight at 510 m indicated less moisture to the northeast of the urban area but little temperature difference. Surface transects found that by 1830 CDT cool air was draining into low areas. Along a transect from Pacific to downtown St. Louis at 1930 CDT, the temperature differential was already $+3.0\text{C}$. On that transect some extremely high dew points were recorded, indicating specific humidities of 15.0 g/kg . These increases could not be attributed to any specific source. Moisture throughout the mixing layer during the daytime and early evening flights ranged from 7.0 to 10.0 g/kg with slightly larger values toward the west. Of

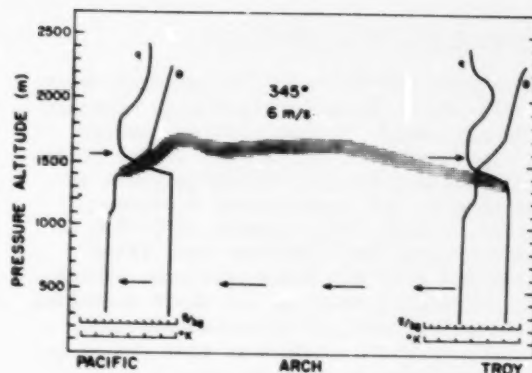


Figure 4.13. Inversion height over St. Louis on 12 August 1971, as measured by aircraft soundings at Pacific (1945 CDT) and Troy (1900 CDT), and horizontal aircraft flights shown by arrows. Soundings show potential temperature (θ) and specific humidity (q) with scales in unit intervals.

cursory interest was a flux of moisture ($\sim 4 \text{ g/kg}$) moving west to east during the day above the inversion, although this flux had no apparent effect on conditions below the inversion.

Aitken counts (Figure 4.14) taken on the 510 m pass measured lower values than the two morning flights. The winds during this last flight were southerly at 2 m sec^{-1} shifting to 345° at 6 m sec^{-1} above 1300 m.

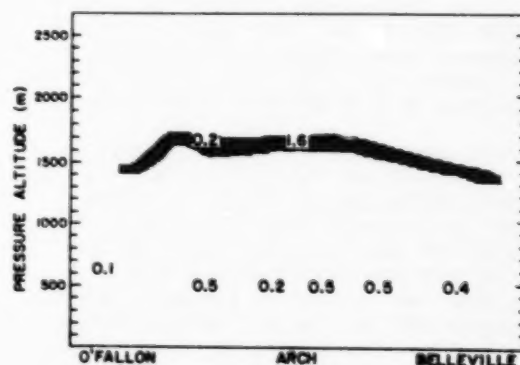


Figure 4.14. Corrected Aitken nucleus concentrations in units of 10^3 cm^{-3} taken during the flight period 1845-2035 CDT, 12 August 1971.

4.3 August 18, 1971, Case Study

Synoptic Conditions. Missouri was under the influence of a weak surface high centered over Pennsylvania. A high pressure center aloft also dominated the central United States. National Weather Service soundings taken at Monett, Peoria and Salem showed a strong inversion at some level between 1200-2200 m. By early evening the inversion had lifted some 500-800 m at all three stations. Winds within the mixing layer at all three locations were south-southwest at approximately 3-5 m sec⁻¹. Upper level winds were from the northwest to northeast at approximately 5 m sec⁻¹. August 18 was declared an air pollution alert day by the National Weather Service in St. Louis. Missouri weather conditions were generally fair all day. A cold front moved into northwest Missouri the morning of August 19.

Morning Measurements. Early on August 18, 1971, the Pacific 0630 CDT sounding had an inversion at 1830 m and the Gateway Arch sounding had an inversion at 1920 m. By 1130 CDT, the two soundings indicated that the inversion over Pacific had subsided 150 m to 1680 m with a slightly stable layer above 1530 m. The Gateway Arch inversion was also at 1680 m with a slightly stable layer beginning at 1530 m. Both soundings were adiabatic from the surface to 1530 m. Thus, during the morning the inversion subsided at both locations. A surface temperature difference of 1.5°C existed between radiosonde sites at 0600 CDT and decreased to 1.0°C at 1200 CDT. This temperature difference measured between the two radiosondes taken at noon decreased to zero at the 1000 m level. During the period 0730-1100 CDT, the SRI lidar took continuous measurements from a downtown St. Louis site which revealed that there were no fluctuations greater than 50 m in the haze layer height.

Winds during the morning were taken at 0600, 0730, 0900 and 1130 CDT at Pacific. The 0600 CDT profile was uni-directional from 160-170° at 2 m sec⁻¹ with a wind shift above 1000 m to 340° at 1 m sec⁻¹. The 0730 and 0900 CDT profiles changed direction with height from 140° to 290° at 1 m sec⁻¹ before shifting to 030° at 5 m sec⁻¹ above 1800 m. The 1130 CDT profile was again somewhat uni-directional from 220-250° at 2 m sec⁻¹ within the mixing layer before changing to 060° at 3 m sec⁻¹ above 1700 m. Wind profiles were measured at the Gateway Arch at 0700 and 1230 CDT. The 0700 CDT profile slowly turned from 130° to 210° at 2 m sec⁻¹ before shifting to 040° at 5 m sec⁻¹ above 1800 m. The 1230 CDT profile was nearly constant with height between the surface and 800 m from 180-200° at 5 m sec⁻¹. No data were taken above 800 m because the haze restricted visibility. A 1230 CDT

profile at Lambert Field was also nearly constant with height from 180-200° at 2 m sec⁻¹ with the highest measurement taken at 1100 m. Winds measured atop the Civil Courts Building (245 m) were southerly at approximately 2-3 m sec⁻¹ during the period 0700-1200 CDT. They slowly increased in speed during the afternoon, reaching a maximum of 7 m sec⁻¹ at 2400 CDT.

Early Afternoon Lidar Measurements.

Measurements taken by the lidar showed that the inversion was domed at 1200 CDT even though a comparison of the Gateway Arch sounding with the Pacific sounding failed to indicate such a dome. Over the Gateway Arch, the haze layer extended to 1530 m but reached 1930 m between the Gateway Arch and Pacific (see Figure 4.15). Transects by the lidar showed uneven inversion heights with sharp fluctuations. The depth of the haze layer increased until it measured 2280 m northeast of St. Louis at 1640 CDT (see Figure 4.16). The lidar data indicated that the inversion dome moderated and the mixing layer deepened in the afternoon similar to that which occurred on August 12. On the lidar transect in Figure 4.15 this trend is already taking place although it is apparent that the mixing layer was definitely higher to the west of the Mississippi River at that time. It should be noted that the rising of the St. Louis inversion could be coincident with the rising of the inversions at Monett, Peoria and Salem.

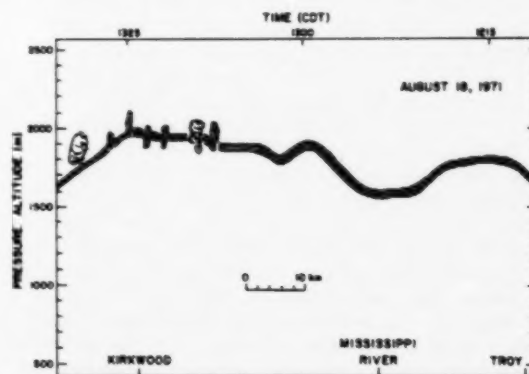


Figure 4.15. A smoothed analysis of lidar measurements of the mixing layer depth along a southwest to northeast line for 18 August 1971. Clouds are shown by the curled etchings.

Aircraft Data. Two aircraft flights were made; one in the late afternoon and the other in the early evening. The soundings made by the aircraft revealed inversions located at 1680 m over O'Fallon and 2140 m over Belleville. Aircraft flight data at 1600 CDT found the air

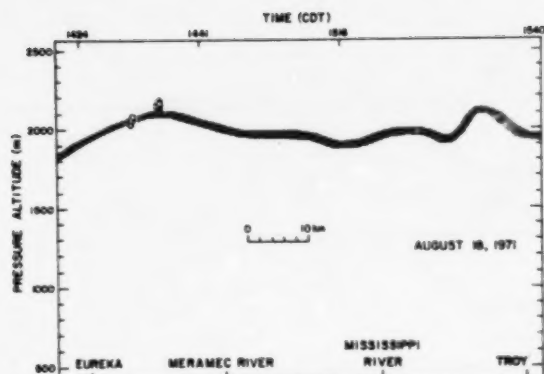


Figure 4.16. A smoothed analysis of lidar measurements of the mixing layer depth along a southwest to northeast line for 18 August 1971. Clouds are shown by the curled etchings.

1.0-1.5 g/kg drier and 0.5K warmer over the city at 520 m and again slightly more moist over the city at 2200 m than over the rural areas with a higher potential temperature (1k) to the northwest of St. Louis. During the late afternoon flight, turbulence values of 2.0-4.0 occurred over the entire length of a 520 m transect while turbulence values of only 0.5-1.0 occurred at 2200 m.

The early evening flight found similar conditions at 520 m with temperatures slightly warmer (~ 0.5 K) over the city than over the rural areas. Of significance though, was the fact that the turbulence meter read nearly zero for the entire transect, reflecting the formation of a stable surface layer. A flight path from northwest to southeast at 1680 m passed out of the mixing layer northwest of St. Louis but then was in the adiabatic layer constantly past Belleville to the southeast. The transect indicated that the inversion was apparently lower than 1680 m to the northwest of St. Louis and tilted upward to the southeast. Aircraft soundings also found the inversion to be above 2150 m southeast of St. Louis at 1900 CDT. Turbulence values of 1.0-1.5 were recorded along the 1680 m transect in the unstable mixing layer.

During both flights, Aitken nucleus counts were periodically taken on board the aircraft and are shown in Figures 4.17 and 4.18. During the period 1500-2000 CDT, the wind measurements taken by the Air Force teams found the mixing layer winds south-southeasterly at 3-4 m sec⁻¹, indicating that the winds had shifted slightly from the 1200 CDT readings. This shift was somewhat reflected in the Aitken nucleus counts. The low-level flight path at 1510-1735 CDT found

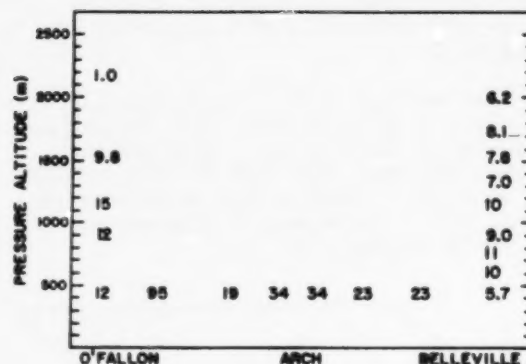


Figure 4.17. Corrected Aitken nucleus concentrations in units of 10^3 cm^{-3} taken during the flight period 1510-1735 CDT, 18 August 1971.

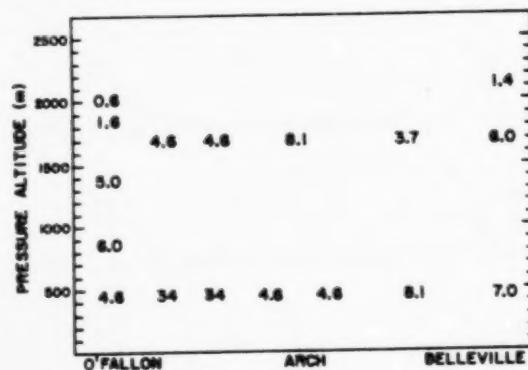


Figure 4.18. Corrected Aitken nucleus concentrations in units of 10^3 cm^{-3} taken during the flight period 1830-2055 CDT, 18 August 1971.

a higher concentration of Aitken nuclei over St. Louis and one extremely high value to the northwest in the Lambert Field or St. Charles area. Aitken nucleus counts taken during the second flight indicated that the low-level pattern had apparently shifted with the more southeasterly wind.

4.4 Partial Case Studies

In contrast to the two days previously considered, August 11 had strong winds of 5-9 m sec⁻¹ within the mixing layer. Strong inversions existed at 1920 m over Pacific and 1840 m over downtown St. Louis at 0630 CDT. Radiosondes taken at 1200 CDT indicated that the Pacific inversion was still at 1920 m while the downtown St. Louis inversion had ascended to 2200 m, resulting in an apparent

dome in the inversion. Synoptic conditions were nearly identical to August 12 except that a cold front had passed about 1800 CDT on August 10.

The 0600 and 1130 CDT winds shown in Figures 4.19 and 4.20 demonstrate the difference between the light wind cases and the strong wind case. The winds at 0600 and 1130 CDT on August 11 were uniform throughout the mixing layer contrasting the disorder at 600-1000 m on August 12.

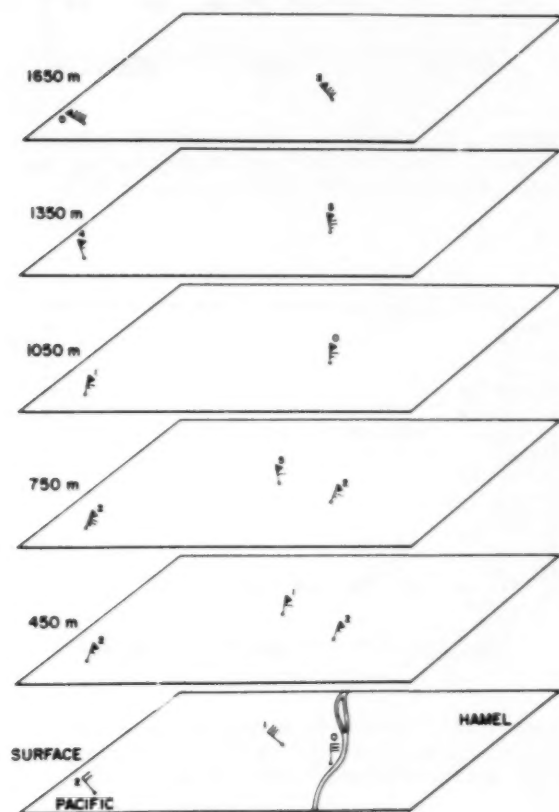


Figure 4.19. Wind profiles for 0600 CDT, 11 August 1971. Each full wind barb is 1 m sec^{-1} and a flag represents 5 m sec^{-1} .

4.5 Results of the St. Louis Airflow Model

The lake effect model developed by Lavoie (1968) was modified at the University of Wyoming in order to obtain qualitative estimates of the importance of friction, terrain and surface heating on urban airflow for Project METROMEX (Auer and Dirks, 1971).

The model assumes the atmosphere is hydrostatic, incompressible and well-mixed in the lower atmosphere capped by a temperature

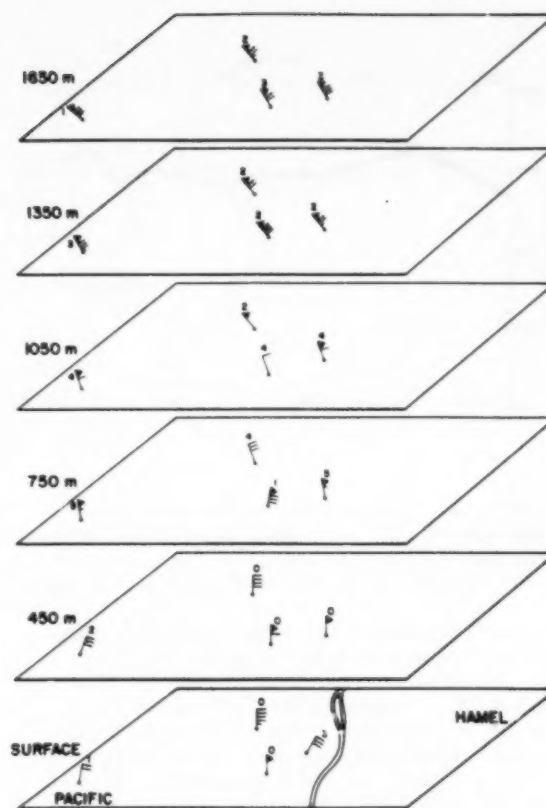


Figure 4.20. Wind profiles for 1130 CDT, 11 August 1971. Each full wind barb is 1 m sec^{-1} and a flag represents 5 m sec^{-1} .

inversion and stable layer. A model having these assumptions would seem to suitably apply to the airflow situations described previously in this chapter. The model computes divergence, horizontal velocity and vertical displacement of the inversion capping the well-mixed layer. The airflow responds to variations in topography, surface roughness and temperature within the friction layer.

The grid used in the model is 39×39 with 2 km intervals expanding geometrically near the boundaries. The geometric expansion extends the boundaries approximately 100 km beyond the urban area and provides a damping effect for the elimination of spurious disturbances resulting from the numerical method.

Terrain height and drag coefficient were evaluated at each grid point. Values of roughness length were computed using an empirical formulation derived by Lettau (1969). The estimated heating field and terrain features used in the model are shown in Figure 4.21.

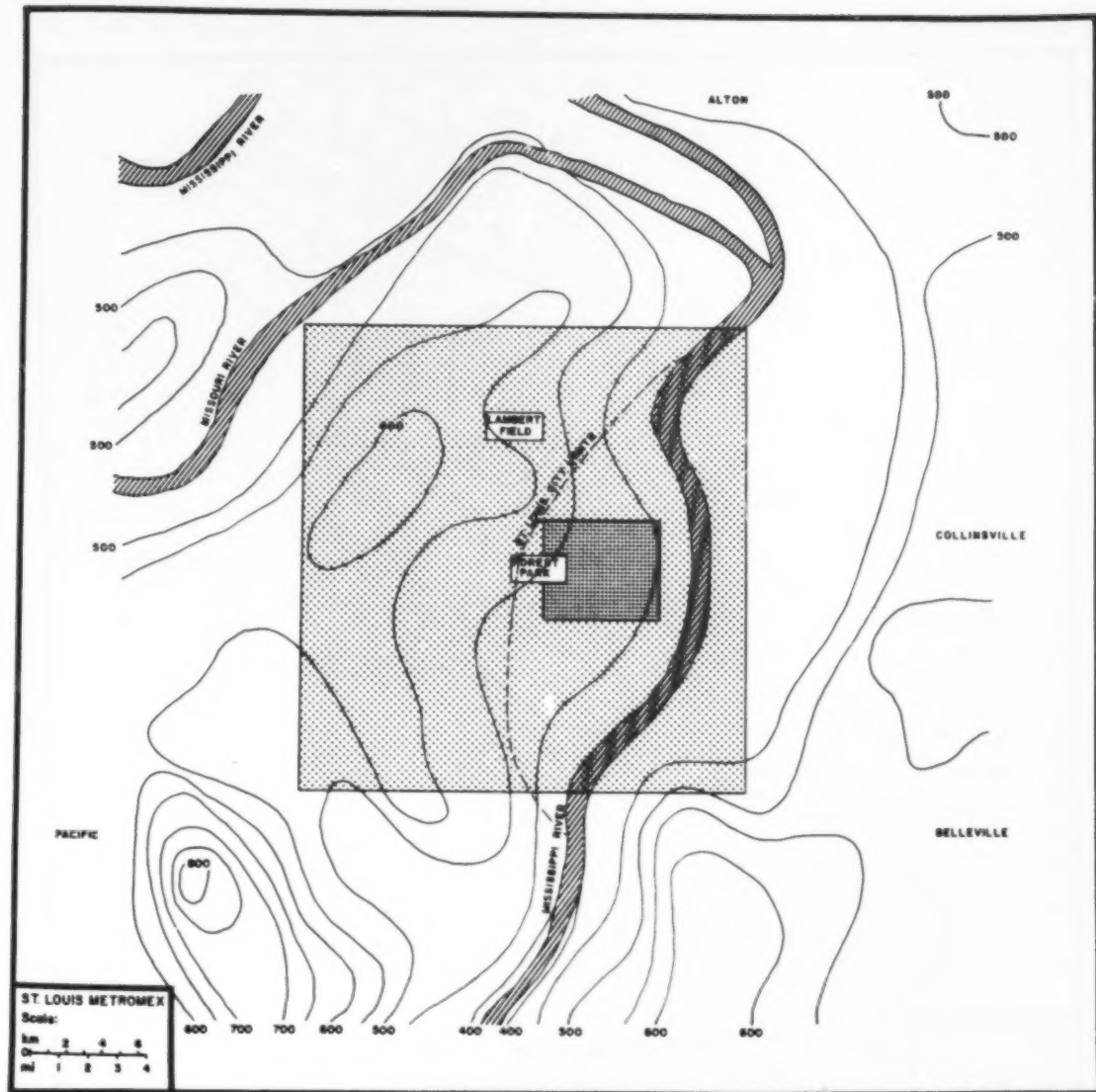


Figure 4.21. Terrain map of St. Louis with contours in feet above sea level. The slightly shaded area is the area of partial heating and the darkest area the region of maximum heating. (A contour interval of 50 feet is used.)

Modeling studies were performed using a typical convective day sounding with a well-mixed layer temperature of 302K, top of the inversion temperature 303K, and capped by a stable layer to 306K. The surface temperature was 302K except where the urban heat island raised that temperature to a maximum of 306K. The results of these studies, shown in Figures 4.22, 4.23 and 4.24, gave estimates of the relative importance of the three forcing mechanisms - friction, terrain and heating - assuming the ambient wind was 135° at 10 m sec^{-1} in the well-mixed layer. Figure 4.22 shows the effect of terrain alone on the

airflow. It appears that the lowering of the inversion level ($\sim 60 \text{ m}$) upwind of the city is caused by the wide river valley. The prominent hill southwest of the city did not produce a significant effect on the airflow (although some noticeable influence was seen with southwest flow).

The effects of 4.0°C maximum surface heating and friction are shown in Figure 4.23 over a flat terrain. These components lift the inversion ($\sim 180 \text{ m}$) downwind of the city and lower the inversion significantly ($\sim 80 \text{ m}$) northeast of St. Louis. When frictional drag

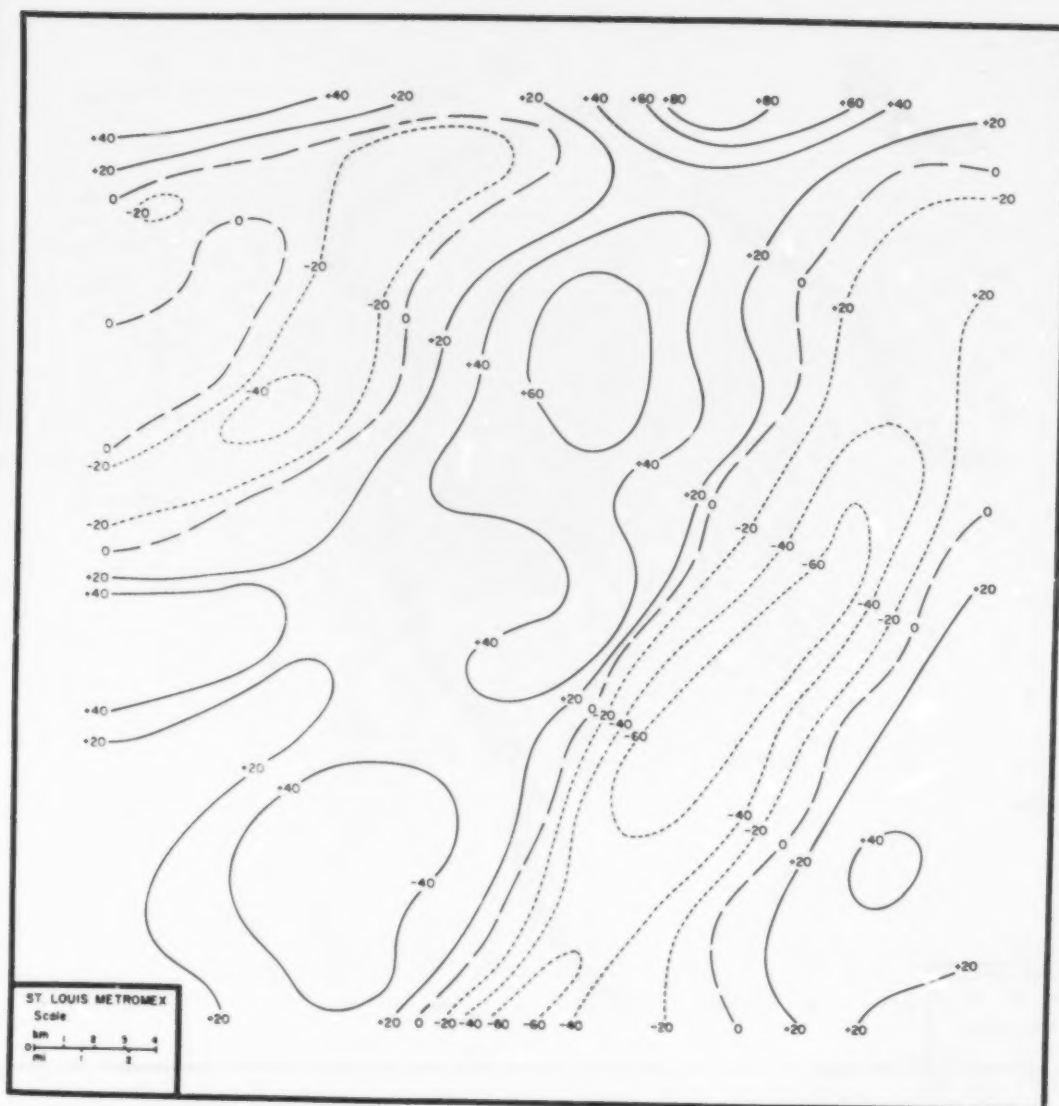


Figure 4.22. Model results after 3600 sec (120 time steps) with terrain height influence only. Solid lines indicate inversion lifting in meters and dashed lines indicate inversion subsidence in meters. Initial wind conditions were 135° at 10 m sec^{-1} .

was tested alone, with no heating and flat terrain, its effect was of the same order as terrain alone. Thus the influence of drag variations are secondary when considered alone, but they may be quite significant in the presence of heating since friction influences the turbulent transfer of heat away from the surface.

Model runs were also made using a lighter wind of 5 m sec^{-1} from 135° and the temperature profile from 1230 CDT on August 12, 1971. The results of those runs showed that the same

relative importance of forcing mechanisms prevailed as in the 10 m sec^{-1} case. The effects of terrain and friction were nearly an order of magnitude less than heating, while heating still exhibited a significant effect resembling that in Figure 4.23. The predicted winds within the adiabatic layer became much more variable in direction with lighter initial wind speeds. After 3600 simulated model seconds, a 0.4K temperature differential existed in the well-mixed layer corresponding closely to temperature differentials measured on August 12 in the well-

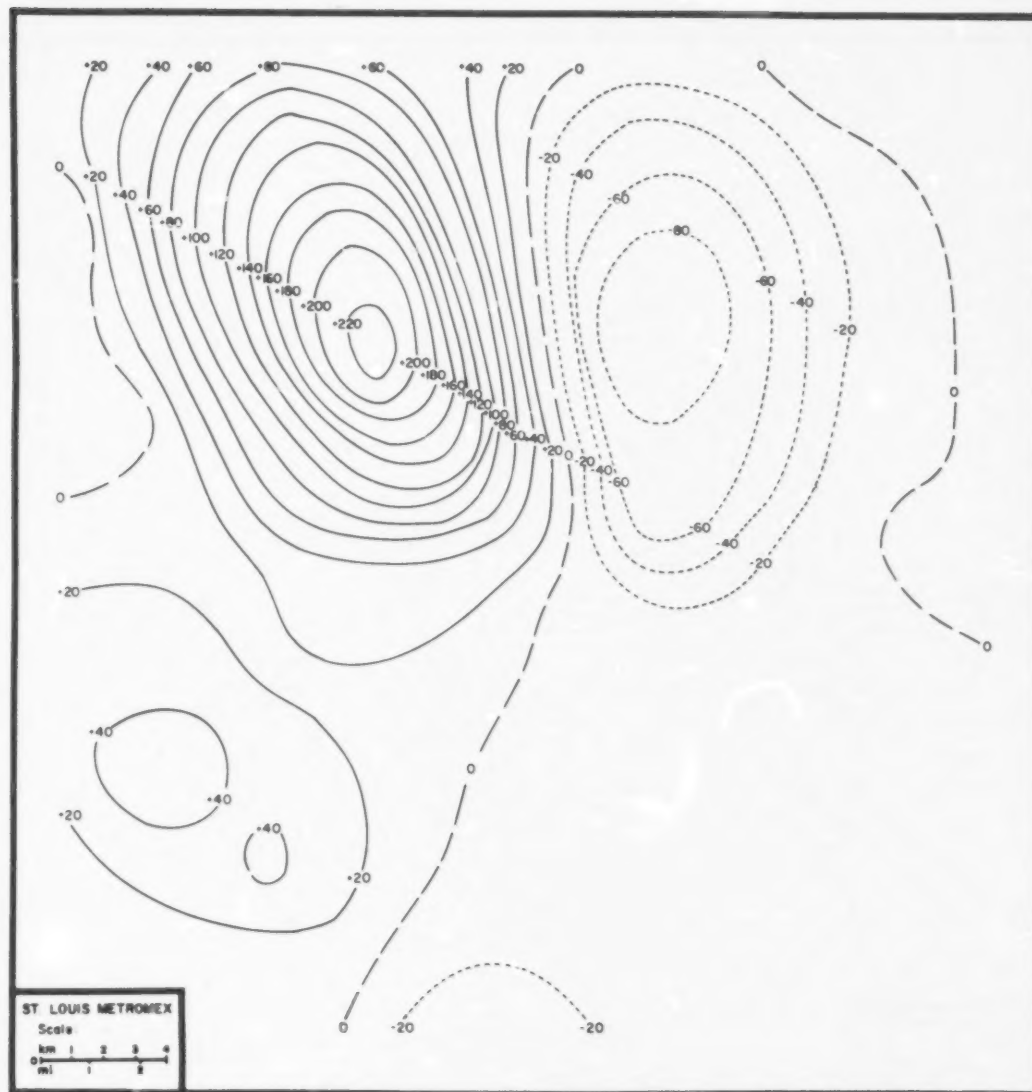


Figure 4.23. Model results after 3600 sec (120 time steps) over flat terrain with friction and heating present. Solid lines indicate inversion lifting in meters and dashed lines indicate inversion subsidence in meters. Initial wind conditions were 135° at 10 m sec^{-1} and the maximum surface heating was 4C .

mixed layer. It is of particular interest to note that a 0.4K temperature differential in the mixing layer of the model resulted in wind fluctuations of 2 m sec^{-1} .

In conclusion, results of the St. Louis airflow model qualitatively indicated:

- a. the presence of an urban heat island of $+4\text{C}$ is sufficient to dominate urban surface influences on airflow over St. Louis;
- b. terrain has a minor influence on airflow over St. Louis;
- c. spatial variations in drag over St. Louis similarly are minor in terms of mechanical effects on the airflow and
- d. thermal differentials of the order 0.4K in the mixing layer may produce significant fluctuations of wind speed and direction.

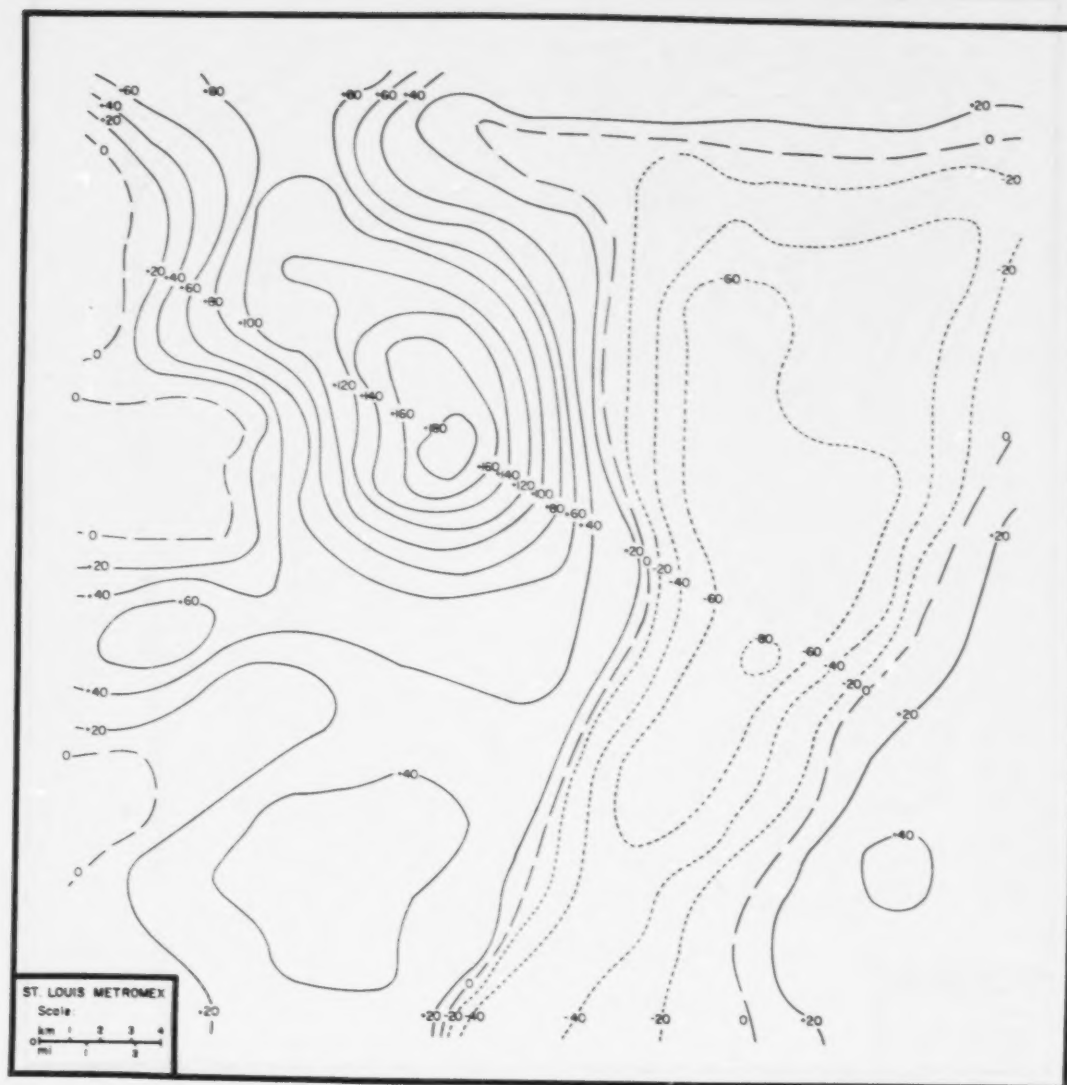


Figure 4.24. Model results after 3600 sec (120 time steps) with terrain, friction and heating present. Solid lines indicate inversion lifting in meters and dashed lines indicate inversion subsidence in meters. Initial wind conditions were 135° at 10 m sec^{-1} and the maximum surface heating was 4C .

V. DISCUSSIONS AND CONCLUSIONS

5.1 General Discussion

The evidence presented in Chapter IV clearly shows a domed temperature inversion capping the mixing layer over St. Louis on August 12 and 18. This meso-scale inversion structure appeared to develop during the morning hours as a result of the inversion subsiding over rural areas as shown schemati-

cally in Figure 5.1. The inversion structure beyond the rural subsidence can only be hypothesized at this time.

Both August 12 and 18 had winds less than 5 m sec^{-1} in the mixing layer. Development of similar urban features, under similar conditions, suggests that common urban influences were present. Other studies in Project METROMEX (Lawson, 1972) found that variations in the height of the temperature inversion

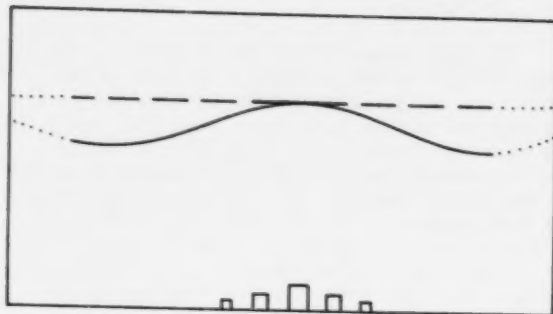


Figure 5.1. Schematic diagram of the daytime inversion structure over a city. The dashed line indicates the inversion position in early morning and the solid line indicates the inversion location at mid-day.

(or stable layer) capping the mixing layer played a significant role in the selective inhibition of convective cloud activity over St. Louis. The inversion dome could therefore form the basis for initial conclusions concerning urban modification of convective precipitation. Although it is not possible to identify the cause of the inversion dome, the role of certain plausible mechanisms can be evaluated.

5.2 Friction

Drag variations have been suggested to have a significant low-level influence over some urban areas, however, the effect of friction on a deep mixing layer is most likely minor in the St. Louis area. Studies by McBean (1968) and Woods (1970) found that mechanical influences of forested areas diminished rapidly within the first 20 m above the forest canopy. Munn (1968) concluded that the significance of mechanically induced turbulence is directly related to the magnitude of the ambient wind. Since forested areas surround St. Louis and most residential areas have numerous trees it is unlikely that the roughness length of the city would greatly exceed that of the rural areas except where there are concentrations of tall buildings (see Section 3.1). Knowing that mechanical effects diminish rapidly with height and that the winds were light during the cases studied it is doubtful that the effects of surface friction significantly influenced the environment at the top of the mixing layer during the August 1971 case studies. Results of the St. Louis airflow model qualitatively confirm this and the uniform low-level winds on August 12 also support this conclusion.

5.3 Topographical Influences

Significant topographical influences on airflow are present in some urban areas such as Los Angeles or those described for Denver by Djordjevic *et al.* (1966). Topographical influences worthy of note in the St. Louis area are localized in the vicinity of the Mississippi River valley with its occasional steep bluffs and the rolling hills to the southwest of the city. Qualitative predictions by the St. Louis airflow model indicated that St. Louis terrain features have only minor influences on an inversion at 1200 m. An application of a similar model by Dirks *et al.* (1970) to an isolated mountain peak found that large scale airflow disturbances were predicted very well, implying some validity for the St. Louis model predictions.

Although the airflow model acknowledges terrain influences on an inversion at 1200 m, they are localized and not of the scale or magnitude of the inversion dome observed over the St. Louis metropolitan area. In addition, winds measured in the lowest 600 m did not reflect significant terrain influences. Consequently, influences on airflow derived from topographical features can be reasonably discarded when considering the inversion dome over St. Louis.

5.4 Waves

A study near La Jolla, California by Gossard and Munk (1954) showed that gravity waves occasionally exist along inversion surfaces. They observed waves of length 4-10 km and phase velocities of 10 m sec^{-1} , greatly exceeding the speed of the ambient winds. Aircraft data from Project METROMEX also gave evidence for the possible existence of short wave length modes as the moisture oscillations on the 1050 m flight level in Figure 4.9 illustrate. However, stationary lidar observations taken on the morning of August 18 revealed that no detectable transient waves occurred over a 3 1/2 hour period (see Section 4.3). These observations eliminate any strong possibility that the inversion dome (~ 30 -60 km across) was the result of a large amplitude gravitational wave.

5.5 Surface Heating

The effects of variable surface heating on airflow have been repeatedly demonstrated by such studies as Malkus (1963), Black and Tarmy (1963), Estoque and Bhuralkar (1969) and Spelman (1969). In the case of an urban area warmer than surrounding terrain, the St. Louis airflow model predicts variations in the height of an inversion on the order of 300 m for an urban heat island of 4°C . These

variations are of the same magnitude as observed in inversion deformations; however, measurements taken in Project METROMEX revealed that daytime thermal gradients were very small at the surface during the month of August. Daytime low-level flights found only small thermal gradients from rural to urban environments. Of some significance is the observation that thermal gradients of the same magnitude (0.5C) were found near the top of the mixing layer. Since heat transfer from the surface is largely a turbulent exchange process, larger horizontal thermal gradients would be expected to occur near the surface.

The observed wind profiles also revealed fairly uniform winds at low levels where surface thermal gradients should cause the most severe perturbations on the airflow. The level of greatest wind variability occurred in the upper part of the mixing layer away from the surface heat source. Wind variations in this region were of the magnitude predicted by the St. Louis airflow model for temperature differentials of 0.4K in the mixing layer. Thus, it is concluded that the effect of a surface urban heat island was not instrumental in causing the meso-scale inversion dome over St. Louis.

5.6 Heating Aloft

The implications of the St. Louis data are that some thermal influence exists within the mixing layer. Thermal influences on the wind fields were noted in the upper levels of the mixing layer bringing to light the possibility that aerosols could be heating up in that region. Atwater (1971) has theoretically shown that at a zenith angle of 90°, 1 ppm of nitrogen dioxide would be heated at the rate of 30C day⁻¹, although his calculation neglects the daily variation in the zenith angle or the probable residence time of aerosols over a city. Since concentrations of 800 ppm nitrogen dioxide are common in automobile exhaust (Hurn, 1968), this type of heating could represent a significant dynamic influence and might be an important contributor to the formation of a daytime meso-scale inversion dome over St. Louis. The apparent development of the dome during morning hours is also consistent with such a heating mechanism. Landsberg (1960) measured 15-20% less solar radiation at the surface in several urban areas than was received in rural areas. Thus, Atwater's calculations have some basis since the solar radiation lost over urban areas may be, in part, absorbed at some level above the surface. Confirmation of the haze layer heating concept needs considerably more data than were available for this study.

5.7 Conclusions

The most significant conclusion of this study is that there existed a daytime meso-scale dome of the temperature inversion capping the deep mixing layer over St. Louis. The dome was found to be a daytime feature, forming during the morning hours and flattening by the early evening. The nocturnal structure was not measured. It appeared that the cause of the meso-scale inversion dome was not associated with surface friction, terrain or surface heating. The cause of the inversion dome, although not known, was most likely located within the mixing layer.

In searching for the urban influence causing the St. Louis precipitation anomaly, haze layer heating should become the object of more extensive study for it has a great capability of exerting a significant modifying influence at the top of the mixing layer. As a part of that study, the theory of Atwater needs physical measurements for verification. If his theory is proved valid, haze layer heating will be a process that deserves serious consideration as a significant dynamic influence of the urban area.

Any urban dynamic influence on mixing layer depth is also of importance to air pollution meteorologists since the depth of the mixing layer effects the concentration of air pollutants. More accurate predictions of the height variation of the trapping inversion would increase the reliability of predicted air pollution levels.

Results of this research may lead to further understanding of the effects of man's urban environment on the processes of precipitation and the quality of the air in that environment. Any advances in the knowledge of these areas may lead to an improvement of the urban environment or at least provide a base from which to improve the knowledge of urban meteorology.

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APPENDIX A. Instrumentation in the University of Wyoming mobile unit. (See Figure A.1.)

Function	Device	Range	System	
			Resolution	Accuracy
Temperature*	Rosemount 104C platinum resistance sensor - ventilated	-50 to +50C	0.1C	+0.2C
Dew Point*	Cambridge Systems Model 880	-40 to +50C	0.3C	+2.0C
Wind speed*	RAIM No. 436 anemometer	1 to 100 mph	2 mph	+5%
Wind direction*	RAIM No. 437 vane	-	16 point	-
Wind sounding	Single theodolite	-	-	-
Atmospheric Pressure	Belfort Model 355 R remote microbarograph	650 to 1050 mb	0.5 mb	Depends on reference
Air filter samples for ice nuclei measurements*	3 x 3 sequential sampler with difference pressure transducer	20 lit min ⁻¹ per filter	-	+5% of volume sampled
Rain drop-size distribution**	Rd-60 momentum sensor	0.3 > D > 10 mm	20 size groups	+5%
Rate of rainfall*	Stand-tube with discharge nozzle	5 > R > 50 mm hr ⁻¹ steady, and R = 200 mm hr ⁻¹ transient	3 mm hr ⁻¹	+5 mm hr ⁻¹ at high R

* Parameters recorded on multipoint strip chart recorder.

** Parameters recorded on analog magnetic tape.

APPENDIX B. Instrumentation on the University of Wyoming aircraft. (See Figure B.1.)

Parameter Measure	Manufacturer and Model Number	Range	Accuracy Sensor / System	Resolution
Temperature	Rosemount Engr. Model 102 de-iced	-50C to +50C	$\pm 1C$ / $\pm 0.1C$	0.1C
Dew Point	Cambridge Systems Model 137-C3	-50C to +50C	$\pm 0.5C$ above 0C $\pm 1.0C$ below 0C	0.1C
Heading	King Radio Model KP1550A	360°	$\pm 2^\circ$ of local magnetic heading / 1°	1°
VOR Azimuth	King Radio Model KNR-660	360°	$\pm 2^\circ$ / $\pm 1^\circ$	1°
DME	King Radio Model KDM-700	0 to 9 nm	± 0.1 nm or $\pm 0.2\%$ or range, whichever is greater / ± 0.1 nm	0.1 nm
Altitude	Ball Model 210B Total pressure Transducer	0 to 25 Kft	0.05% / 0.1%	continuous
IAS	Rosemount Model 1301D Differential Pressure Transducer	0 to 250 Kts	± 2 Kts / ± 1 Kts	1 K
Manifold Pressure	Computer Instruments	15 to 30" Hg	5% / $\pm 0.1\%$	0.1" Hg
Vane angle or angle of attack	U. W. Atmospheric Research Group	99°	2% / 2%	0.1°
Pitch Angle	Smith Industries Lmt'd - Aviation Division Model 402RGS/-2	0 to $\pm 20^\circ/\text{sec}$	2% / 2%	$0.04^\circ \text{ sec}^{-1}$
Roll Angle	Smith Industries Lmt'd - Aviation Division Model 402RGS/-2	0 to $\pm 20^\circ/\text{sec}$	2% / 2%	$0.04^\circ \text{ sec}^{-1}$
Vertical Acceleration	United Controls Model No. 2152	± 3 g's	1% of full range	0.006 g's
Liquid Water	Johnson Williams Model No. LWH	0 to 3 gm m ³	unknown / ± 0.1 g m ⁻³	0.1 g m ⁻³
Turbulence	M. R. I. *			
Ice Nuclei	Membrane Filters			

* The Meteorology Research Incorporated turbulence intensity meter measures a density corrected $\epsilon^{1/3}$. ϵ is the equilibrium rate at which energy enters the system, flows to smaller eddies and leaves the system through viscous heating. MacCready (1964) gives the following description of turbulence intensity values: 0-0.7 negligible (to aircraft occupants); 0.7-1.5 light turbulence or bumpiness; 1.5-3.5 moderate turbulence and 3.5-8.5 heavy turbulence (found in developed cumulus clouds).



Figure A.1. University of Wyoming Mobile Meteorological System.



Figure B.1. University of Wyoming Instrumented Aircraft.